REMOTE SENSING OF INTENSITY AND ORGANIZATION OF CONVECTION IN HURRICANES AND TROPICAL CYCLONES BEFORE AND AFTER LANDFALL, AND APPLICATION TO QUANTITATIVE PRECIPITATION ESTIMATION

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ABSTRACT

This proposal involves active participation in the CAMEX-4 field program as one of the deputy mission scientists, with close cooperation with many other investigators in the field and during the data analysis and research phases. The model established during the CAMEX-3 field program worked well, with two deputies sharing on-site and airborne responsibilities with the CAMEX Mission Scientist, in close daily coordination with NOAA's hurricane research division.

The overarching scientific objective of this proposal is to observe and explain how the strength and structure of convection in a hurricane changes during and after landfall. The main applied goal of this proposal will be to use this knowledge to develop improved methods for using remote sensing data (mainly radar and passive microwave data) for quantitative precipitation estimation (QPE). The combination of EDOP (Doppler radar) and AMPR (passive microwave) data from the NASA ER-2 is extremely powerful. Using such data from CAMEX-3 and the field programs for TRMM validation, the PI, together with students and colleagues, has been evaluating sensitivity of retrievals to ice water content and particle size and density distributions. It is important to compare the diagnosed and observed microphysical properties. Despite some notable successes, there were relatively few opportunities to bring the necessary resources to bear in landfall situations.

In addition to targeting landfalls, it makes sense to have alternative targets available during intervals of CAMEX-4 without named storms in range of the NASA aircraft. It will be most valuable if those targets are also observed by Doppler and multi-parameter surface-based radars, and by profilers. Where feasible, direct sampling of microphysical properties should be included, whether by a dedicated aircraft or by one of the NOAA P-3s. Coordinated overflights of heavy rainfall systems by the ER-2 can be applied to the QPE problem, for those occasions when WSR-88Ds and satellites are the only tools available to weather and river forecasters. The current state-of-the-art of QPE using the WSR-88Ds alone or using satellite data needs improvement, whether in named tropical cyclones or not.

1. Accomplishments under current WRP/CAMEX grant (NAG8-1491)

This was a joint award to the PI, then of Texas A&M University, and Gerald Heymsfield of NASA GSFC, with co-I's Robbie Hood and Richard Blakeslee of NASA MSFC. Although the PI moved to the University of Utah during year-2 of this grant, it continues to be administered through Texas A&M for the convenience of the Ph.D. student Daniel Cecil who is scheduled to defend his dissertation in October 2000.

The PI was also responsible for coordination of the TRMM validation field campaigns, including the TExas-FLorida UNderflights (TEFLUN) in 1998, and major programs in Brazil (Jan-Feb 1999) and Kwajalein (Jul-Sep 1999). The instrument packages planned for TEFLUN and CAMEX were nearly identical. It proved possible to combine these two programs to their mutual advantage, using Patrick AFB for all participating aircraft, and setting up NCAR's S-POL radar a short distance away to support the investigations of precipitation systems over land and ocean. The synergy of these two programs was both scientific and operational. Scientific, because a far larger database of precipitating systems was obtained which related well to one another. Operational, because during periods of several weeks each without suitable tropical cyclone targets, convective systems were available most days in the operating area.

"*Coordination with other components is ESSENTIAL!* We enthusiastically accept the need for full cooperation with the other investigators who are involved in observation of hurricanes before, during, and after landfall in the interests of obtaining a comprehensive database for all. We will apply our experience during TOGA COARE and many other programs for the benefit of this one."

The above statement, extracted from our joint CAMEX-3 proposal, was important in 1998 and it will be equally important for CAMEX-4. We expressly entered into the closest possible coordination with NOAA's Hurricane Research Division (HRD), and it resulted in successful joint aircraft missions in Bonnie (21, 23, 24, 26 August), Danielle (29, 30 August) and Georges (21, 22, 25, 27 September). The working relationship that was established between NOAA and NASA scientists and flight operations personnel alike is a strong base upon which to build CAMEX-4. An additional benefit accrued to students, who gained experience flying on both NOAA and NASA aircraft and interacting with both sets of scientists.

Refereed Publications

Nesbitt, Stephen W., Edward J. Zipser, and Daniel J. Cecil, 2000: A census of precipitation features in the Tropics using TRMM: radar, ice scattering, and lightning observations. *J. Climate*., **13**, in press.

Cecil, Daniel J. and Edward J. Zipser, 1999: Relationships between Tropical Cyclone Intensity and Satellite-Based Indicators of Inner Core Convection: 85-GHz Ice-Scattering Signature and Lightning. *Mon. Wea. Rev.*, **127**, 103–123.

Papers Presented At Meetings

Lawrence, James R., Stanley D. Gedzelman, and Daniel J. Cecil, 2000: Stable isotope ratios of water vapor as a signal of mesoscale convective activity. Special Session A10, Results of TRMM Field Campaigns, Fall Meeting, Amer. Geophys. Union, San Francisco, CA.

Cecil, Daniel J., 2000: Reflectivity, ice scattering, and lightning characteristics of tropical cyclone eyewalls, inner rainbands, and outer rainbands. *24th Conference on Hurricanes and Tropical Meteorology*, American Meteorological Society, Ft. Lauderdale, FL, 412-413.

Cecil, Daniel J., Edward J. Zipser, Gerald M. Heymsfield, Robbie E. Hood, and Monte G. Bateman, 2000: An investigation of precipitation structures in Hurricane Bonnie. *24th Conference on Hurricanes and Tropical Meteorology*, American Meteorological Society, Ft. Lauderdale, FL, 183-184.

Cecil, Daniel J. and Edward J. Zipser, 1999: Reflectivity, ice scattering, and lightning characteristics of hurricane eyewalls and rainbands. *TRMM - GPM Meeting*, College Park, MD.

Cecil, Daniel J. and Edward J. Zipser, 1999: Distributions of radar reflectivity profiles and microwave brightness temperatures observed in tropical cyclone eyewalls and rainbands. *29th International Conference on Radar Meteorology*, American Meteorological Society, Montreal, PQ, 386-389.

Cecil, Daniel J., 1999: Tropical cyclone eyewalls and rainbands through the eyes of the TRMM satellite. *23rd Conference on Hurricanes and Tropical Meteorology*, American Meteorological Society, Dallas, TX, 1001-1003.

Nesbitt, Steven W., Edward J. Zipser, and Daniel J. Cecil, 1999: A census of precipitation features in the Tropics using TRMM: radar, ice scattering, and lightning observations. *TRMM - GPM Meeting*, College Park, MD.

Wolff, David B. and Daniel J. Cecil, 1999: Comparison of ground-based and TRMM Precipitation Radar reflectivity fields over Texas and Florida. *23rd Conference on Hurricanes and Tropical Meteorology*, American Meteorological Society, Dallas, TX, 949-950.

Zipser, Edward J. and Daniel J. Cecil, 1999: Multi-parameter investigation of the convective structures in Hurricane Bonnie at landfall. *First USWRP Science Symposium*, Boulder, CO.

Cecil, Daniel, David B. Wolff, E. Richard Toracinta, and Stephen W. Nesbitt, 1998: Multi-sensor comparison of TRMM satellite and ground validation products from Texas and Florida squall line events. *19th Conference on Severe Local Storms*, American Meteorological Society, Minneapolis, MN, 587-590.

Cecil, Daniel J., 1998: Is inner-core lightning an indicator of tropical cyclone intensification? *Symposium on Tropical Cyclone Intensity Change*, American Meteorological Society, Phoenix, AZ, 93-94.

Pending: Ph.D. dissertation, Texas A&M Univ., consisting of the following two manuscripts to be submitted to *Mon. Wea. Rev*. by December 2000, co-authors TBD.

Cecil, Daniel J., 2000: Reflectivity, ice scattering, and lightning characteristics of hurricane eyewalls, inner rainbands, and outer rainbands. Part I: Quantitative description.

Cecil, Daniel J., 2000: Reflectivity, ice scattering, and lightning characteristics of hurricane eyewalls and rainbands. Part II: Intercomparison of observations.

The above list summarizes the accomplishments of Dan Cecil during the past 3 years, but also is evidence of the close relationship of his work to the other students of the PI supported elsewhere, mainly by NASA TRMM funding.

We have approached the scientific problems from two directions. One is to carefully analyze specific case studies, such as the Bonnie landfall on 26 August 1998. The second is to obtain a statistical background against which these (rare) case study opportunities can be placed. The goal is to understand how to interpret the apparent differences between eyewalls, and inner and outer rainbands, which will prove useful in anticipating changes in intensity and rainfall in landfalling cyclones.

The PI's group has assembled a database from TRMM consisting of all precipitation features (PFs) observed by the precipitation radar (PR) greater than 4 contiguous pixels. The scheme is described in Nesbitt et al (2000). The unique feature of this approach is that it is possible to isolate subsets of features by their size, rain volume, radar profiles, ice scattering signatures, lightning flash rate, etc. For example, in agreement with findings of Chen and Houze (1997) and Laing and Fritsch (1997) using IR data, preliminary results by Nesbitt (personal communication) show that the larger mesoscale convective systems (MCSs) peak from midnight to early morning over both land and ocean.

Cecil has assembled a subset of this database for 261 TRMM passes over 45 hurricanes or tropical cyclones. It consists of TRMM Microwave Imager (TMI) ice scattering signatures and TRMM PR reflectivity profiles and Lightning Imaging Sensor (LIS) flash locations for the rain features associated with all tropical cyclones observed by TRMM from Dec. 1997 through Dec. 1998. Each rain feature has been subjectively cataloged as belonging to a hurricane eyewall, inner rainband, outer rainband, or the inner or outer regions of a developing or non-developing tropical cyclone. This database quantifies the *relative* abundance of lightning in outer rainbands compared to eyewalls and inner rainbands. Despite the difference in lightning frequency, distributions of observed ice scattering signatures are fairly similar for eyewalls and outer rainbands. Inner rainbands produce the least lightning. Consistent with this, inner rainbands are dominated by stratiform precipitation. That convection which does occur in the inner rainbands tends to be less intense (in terms of both ice scattering signatures and reflectivity profiles) than that found in either the outer rainbands or the eyewalls. The outer rainband and eyewall categories contain ice scattering signatures and reflectivity profiles comparable to those found in a general (non- tropical cyclone) tropical oceanic sample. This sample contains less lightning than the hurricane outer rainbands, in agreement with Molinari et al. (1994), and Samsury and Orville (1994). The TRMM data set permits studies that can seek more specific physical relationships than Cecil and Zipser (1999) were able to find when they related some SSM/I measures of ice scattering to hurricane intensity change.

All of these hurricane and tropical oceanic categories produce dramatically less intense convection than that found in a tropical continental sample. Besides producing much greater ice scattering signatures and reflectivity profiles, the continental sample exhibits a much greater probability of lightning *for a given ice scattering signature* compared to the oceanic categories. Among the oceanic categories, the outer rainband sample exhibits the greatest probability of lightning for a given ice scattering signature. Toracinta (personal communication) is also finding *that for a given PR profile*, there is a greater probability of lightning over land than for any ocean or tropical cyclone category. Now, Cecil finds that that *for the identical TMI (Fig. 1) and PR parameter space, outer bands have a higher probability* *of lightning* than eyewalls or the general ocean data set. While this is puzzling and must be investigated further, it strongly suggests that *lightning data can add independent information to passive microwave and radar data.*

2. Specific scientific objectives for CAMEX-4

Background -- a Bonnie 1998 example. Despite the many notable successful flights in CAMEX-3, the data sets obtained during landfall events had some important deficiencies. The flight patterns were intentionally designed to cover all quadrants of the hurricane. The flights for Bonnie's landfall on 26 August were timed to coincide with TRMM overpasses, which all took place several hours before the center of the storm crossed the coastline. One of the best-coordinated flight legs was from NE to SW from 1449-1511 UTC, with the TRMM overpass at 1450 (Fig. 2). Note the lightning close to the aircraft track in the SW eyewall. This is an area of elevated reflectivity on EDOP and 85 GHz Tb depression to about 210°K, yet there is a bright band and the elevated reflectivity is quite uniform in the horizontal over about 50 km (Fig. 2). Rather than a continuously sloping eyewall, the cross-section seems to show a disconnect between intense low-level echo (at 1506) and the enhanced reflectivity aloft (1510-14).

What is the explanation? Were there intense convective cells rotating around the eyewall 10-20 minutes earlier (perhaps the one due south of the eye on the TRMM PR image, or transient cells already dissipated) which produced the ice hydrometeors crossed by the aircraft? Or is there a quasi-steady 1-3 m s^{-1} updraft persisting for perhaps hours? Or both? A single set of aircraft cross-sections cannot answer such questions. Nor is there any microphysics sampling taking place below 10 km.

But these are important questions. For quantitative precipitation estimation (QPE), a WSR-88D radar at a range of 220 km (as in this case) has a beam width of 3.6 km and a radar horizon of 3 km above sea level. Therefore, even within the nominal range of the Wilmington 88D, we cannot use the radar sequence to put the aircraft snapshot in the proper context of the evolution of this large eyewall structure. If one were using passive microwave estimates from space, the low frequencies might give good estimates over the ocean (ignoring important non-uniform beam-filling problems). Over land, and over complex terrain where the 88Ds have serious well-known problems, the high frequency channels (mainly 85 GHz) would be the principal tools for diagnosing the vertical profile of precipitation, but they respond mainly to ice and not to the rain beneath the ice (Fig. 2). We have much to learn about the interpretation of the scattering signature. The addition of lightning information may provide important hints, as in this case, that strong convection contributed to the elevated ice mass. As in Vivekanandan et al. (1991) we may be able to conclude that higher density ice is necessary to explain the low Tb at 85 GHz. However, this will require working with cloud ensemble models as well as radiative transfer models, and the observational data needed to validate the models is inadequate, even in this excellent example from Bonnie.

We shall endeavor to obtain a few data sets in CAMEX-4 that are closely focused on specific convective features. The most important requirement is for more frequent sampling of the targeted precipitation features. The target should be within 150 km of ground-based radar.

Aircraft plans should include an optional module for repeated sampling of the same target, such as was done in several of the TRMM field campaigns. If the situation permits, a microphysics aircraft should sample beneath the NASA ER-2 and DC-8, to obtain the radar, microphysics, passive microwave, and electric field measurements in the time-space domain.

Specific flight scenarios must be developed in cooperation with all CAMEX investigators, including HRD scientists. There must be enough variety in the types of targets to have viable objectives that suit the conditions presented by nature. In the event of a well-defined eyewall coming onshore, repeated crossings of the eye will probably take precedence.

The goals of improving QPE can be pursued in a variety of situations. Excessive rainfall in tropical cyclones often comes from MCSs in outer bands. Some of the greatest rain events are not associated with eyewalls or have come from storms in sub-hurricane or tropical depression stages (Marks et al. 1998, Fritsch et al. 1998). Examples include Diane 1955, Camille 1969, Agnes 1972, Amelia 1978, Claudette 1979, Alberto 1994, Danny 1997, Charley and Frances 1998, Dennis, Floyd and Irene 1999. Therefore, it is possible that many of the objectives related to QPE and interpretation of remote sensing data through improving cloud, microphysical, and radiative transfer models can be met by choosing appropriate MCS targets outside of eyewalls, especially in weaker storms. Progress toward these goals can also be made during alternate missions planned during periods without tropical cyclones (see Objective 4).

Objective 1a. Obtain a high-resolution database of specific MCS structures in tropical cyclones near or over land. Repeat sampling several times per hour over 1-3-hour periods, such that the cases can be used as validation data for cloud and radiative transfer models. Include as many of the following components as possible in any given situation:

- ER-2 and DC-8 overflights with Doppler radar and multifrequency passive microwave radiometry on both aircraft. If safe and possible, microphysical sampling from DC-8. From offshore locations, dropsondes from DC-8 and if available, from ER-2.
- NOAA WP-3D flight tracks covering MCS target with tail radar, cloud microphysics sampling at a range of altitudes, and in situ meteorological data.
- Surface-based multiple-Doppler radar coverage of target system for continuous monitoring of convective and stratiform components.
- Polarimetric radar coverage of target system for support of hydrometeor phase and rainfall estimates in support of microphysical modeling and parameterizations.
- Enhanced boundary layer profiling and supplemental soundings, for intrinsic understanding and for initialization of cloud ensemble models.

Objective 1b. Bring several case studies from TEFLUN and CAMEX-3 to a conclusion (first year) and undertake analysis of cases from CAMEX-4 (year 2 and 3). This is a cooperative effort among many PIs. The particular focus of our work at Utah will be to build on the database created by Cecil, and assessing how the specific eyewalls, inner rainbands, and outer rainbands of CAMEX compare in convective strength to the larger population. We are planning joint cloud ensemble modeling of case studies, providing input and validation data.

Background – Using concurrent radar and microwave data to constrain microphysical profiles

The combination of radar reflectivity profiles and passive microwave brightness temperatures (Tb) is potentially very powerful. The PR and TMI on TRMM have already yielded a database of millions of such combinations throughout the tropics. During CAMEX and the TRMM field campaigns, this combination has been available, but at very much higher resolution, from EDOP and AMPR on the NASA ER-2 (Heymsfield et al. 1996, Geerts et al. 2000). The idea of using this combination to derive precipitation profiles is not new. However, most techniques begin with an array of Tb from the radiometer data, using radar profiles mainly as validation data (e.g., Olson et al. 1996, 1999). One element of this type of approach is to use a Bayesian technique to seek the closest match between the *observed* Tb array and the large set of Tb arrays *simulated* by applying a radiative transfer model to the output from a cloud ensemble model. The hydrometeor profile in the cloud model at that point in space/time is taken as the solution. The extent to which the radar profile from that solution matches an observed radar profile is one approach to validation of the method.

An alternative approach, with its own obvious shortcomings, is to bypass the (imperfect) cloud models with their (imperfect) microphysics parameterizations. One can take advantage of the observed radar profile to derive (guess!!) a profile of hydrometeor phase, density and size distribution. We are beginning by using the radar/ice relationships of Black (1990) for hurricanes, taking convective/stratiform fraction into account. One then can use these to drive a radiative transfer (RT) model. We are beginning this approach using the plane parallel RT model similar to that of Kummerow (1993), comparing the *observed* Tb array to the *simulated* Tb array. We are also preparing to use a Monte Carlo backward RT model for convective situations where the plane parallel assumption is likely to yield large errors (Kummerow 1998).

Only one example is presented here, not entirely appropriate for CAMEX because it is from an ER-2 overflight of an intense convective line over the Florida peninsula during TEFLUN, far too intense to consider penetration by any of the available aircraft. Thanks to Robbie Hood for the AMPR data and Gerry Heymsfield for the EDOP data, Chris Kummerow for use of his RT model, and Baike Xi and Steve Nesbitt (both supported by the PI's NASA TRMM grant) for adapting the model and doing the computations. Figure 3 shows the comparison between the observed and simulated Tb profiles at 85 GHz (other frequencies not shown). Not surprisingly the simulated Tb is highly sensitive to the assumed ice particle density (e.g. Vivekanandan et al. 1991). Best fit is for density between 0.1 and 0.4. This is very simplistic for many reasons, and the regions of agreement can well be from compensating errors. For example, we may believe that in the weaker parts of the system that 0.1 may be a reasonable density. In the very intense cell, we may expect large high density graupel and hail, and it is quite possible that emission from supercooled liquid water partially masks the ice scattering (Adler et al. 1991, Vivekanandan et al., 1991).

Objective 2. Use data from comprehensively sampled case studies from CAMEX-4 to seek relationships between radar profiles and ice particle density and size distributions that permit good agreement between observed and simulated Tb arrays. Evaluate sources of uncertainty, using concurrent data from *in situ* microphysical aircraft, and polarimetric radar. Use this more comprehensive data set to evaluate the constraints on the very imperfect radar–hydrometeor relationships.

Objectives 1 and 2 outline some of the scientific focus of our research group at the University of Utah, using the data from CAMEX. These research areas necessarily require interactions with our closely related TRMM research, and extensive collaborations with such outside scientists as F. Marks, G. Heymsfield, R. Hood, A. Heymsfield, J. Dye, R. Black, P. Willis, M. Biggerstaff, H. Christian, C. Kummerow, W. Olson, W.-K. Tao and others, but they point toward papers for which our group expects to take a lead. The remaining objectives outline elements of CAMEX-4 which are deemed necessary for success of the program as a whole, and for which the PI proposes to undertake an active but primarily supporting role.

Objective 3. Participate in the CAMEX-4 field program, in whatever role is most useful, but perhaps as one of the deputy project scientists. Assist on board the DC-8 is desired during hurricane missions. Assist in planning and coordination of all joint missions with the designated lead scientists for NOAA/HRD. For potential landfall missions, the coordination with the fixed and mobile surface-based observing facilities will be complex. Advance planning will be needed to assure both the safety and effectiveness of these facilities during landfalls. A particularly difficult problem will be the real-time communication with and between the aircraft fleet if the desired database is to be obtained. Experience has shown that the on-board radars on the DC-8 and (for example) the UND Citation are adequate for navigating with respect to an eyewall, or for storm avoidance, but not for coordinated flights with respect to MCSs.

Objective 4. Participate in the development and implementation of a coordinated aircraft and land-based observing program which will target precipitation systems for study within one hour flight time from the CAMEX NASA aircraft base (nominally Homestead AFB). For purposes of this proposal, it is assumed that CAMEX-4 will include such a component, similar to the Keys Area Microphysics Project (KAMP) proposed by Mike Biggerstaff and a large group of co-investigators.

The PI strongly supports the position that CAMEX-4 *needs* a fixed array of surface-based radars, Doppler and polarimetric, boundary layer profiling, and at least one dedicated aircraft for in situ microphysics and also radiometric and electric field measurements. The specific locations proposed for KAMP are not magical but they have been surveyed and they are probably the best available (Fig, N). Facilities that have been proposed include dual-Doppler 5-cm radars (Biggerstaff), NASA polarimetric S-band radar (Gerlach), X-band polarimetric radar and video disdrometer (Anagnostou and Vivekanandan), boundary layer profiling (Knupp), and microphysics aircraft (Geerts, Poellet and A. Heymsfield, Christian, others).

It is important to WRP/CAMEX-4 goals that when a tropical cyclone is predicted to affect land that the more mobile of these observing capabilities deploy in suitable sites near the landfall location. (Some of the proposed KAMP facilities will require evacuation in the event of a hurricane threat to the Keys. This is also an issue for the aircraft, depending upon the final choice of aircraft base.) Advance planning is essential as well as careful weighing of options during the field campaign. Best case scenario is that predictions will be good, and the mobile facilities can redeploy from the Keys to (e.g.) Mississippi or North Carolina within 2 days, and that all CAMEX aircraft can support the landfall experiments.

There are also some not-so-good scenarios. One is that there will be no suitable landfall cases at all, or a small number of marginal cases for which circumstances conspire to make a successful deployment very difficult. Even in a normal year (2 landfalls during the planned CAMEX period), there are many advantages to having a predictable, convenient instrumented location for NASA ER-2 and DC-8 overflights during CAMEX for precipitation experiments. Hurricane landfalls (see Bonnie example above) often force constraints on the flight patterns which result in less well-focused data sets for certain goals (i.e., not all masters can be served). Last but not least, even in hurricane-rich years like 1998, several weeks often pass with no tropical cyclones within reach of the NASA aircraft. During such periods, an alternate target is highly desirable, and as in the CAMEX/TEFLUN experience, will serve the scientific needs without straining available resources. Scientifically, it is now quite clear that the goals of CAMEX relating to QPE can be pursued almost as well through study of precipitation systems outside of the tropical cyclone environment. The issues of interpreting radar and passive microwave measurements in terms of the microphysics are reasonably similar.

EXPECTED RESULTS AND MANAGEMENT PLAN

Year 1 (March 2001-Feb. 2002). Several case studies from TEFLUN and CAMEX-3 should be brought to a conclusion. Build on Nesbitt's and Cecil's database of TRMM precipitation features and hurricane features, and place the CAMEX cases into that perspective. Nesbitt and Xi train new graduate research assistant in use of the database and RT model. The PI also assists in CAMEX-4 planning. PI and grad assistant spend approx. 6 weeks each in the field.

Year 2 and 3. PI assists in CAMEX-4 data QC, analysis, and selection of cases and data sets for archival. (This requires much coordination and diplomacy, one learns.) Research associate (Xi), grad assistant, and PI complete development of cooperative projects for data analysis, and for cloud ensemble and RT modeling using better case studies for initialization and validation. We are planning joint cloud ensemble modeling of case studies, providing input and validation data. As outlined above, extensive collaboration with most of the named colleagues will be necessary. The role of our participation is not to create new models or retrieval schemes, but to work together with other participants to help diagnose the degree of validity of the results.

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